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STUDIES OF OXIDANT TRANSPORT BEYOND URBAN AREAS
New England Sea Breeze - 1975

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16 ABSTRACT

Relationships between ambient air quality and sea breeze conditions in southern New England are examined. In the Boston area, sea breeze conditions were observed on approximately 25% of the days of the study (July-August 1975). The sea breeze effect can either moderate or enhance the pollution levels in the Boston area. However, the most common course for the sea breeze is to have a cleansing effect. Therefore, ozone levels are generally lower during sea breeze conditions.

In the Groton area of Connecticut, a well-developed sea breeze effect was observed almost daily. High ozone concentrations usually coincided with a sea breeze effect. Measurements from aircraft over Long Island and the Atlantic Ocean show that air pollutants are advected into the Groton area by the sea breeze. The pollutants over the ocean were part of the large urban plume originating in the New York City-New Jersey area.

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STUDIES OF OXIDANT TRANSPORT BEYOND URBAN AREAS
New England Sea Breeze - 1975

by

H. Westberg, K. Robinson, D. Elias and K. Allwine
Air Resources Section
Chemical Engineering Department
Washington State University
Pullman, Washington 99164

Contract No. 68-02-2230

Project Officer

Joseph J. Bufalini
Atmospheric Chemistry and Physics Division
Environmental Sciences Research Laboratory
Research Triangle Park, North Carolina 27711

ENVIRONMENTAL SCIENCES RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NORTH CAROLINA 27711

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ABSTRACT

The relationship between sea breeze winds and ambient ozone concentrations in two areas of southern New England is examined in this report. Air quality along the Connecticut coast is strongly affected by a well developed sea breeze because this system provides a mechanism for transporting the urban plume from the New York City-New Jersey complex over coastal Connecticut. It is apparent that air pollution control strategies for southern Connecticut must recognize the advection of pollutants by the sea breeze. In the Boston area, sea breeze situations are not as common or as extensive as observed along the Connecticut coast. Arrival of the sea breeze at a Boston area station was usually associated with a decrease in ozone concentration. Data used in this analysis was collected during the summer of 1975.

PREFACE

During the Summer of 1975, Washington State University participated in an extensive air pollutant monitoring program in New England. Primary objectives of the field program were to monitor ozone and ozone precursors over specific parts of the New England region and determine to what extent the oxidant problem in the Boston area is attributable to transport. Specific topics to be considered included: (1) oxidant formation and transport within the Boston and New York City urban plumes, (2) oxidant behavior in relation to high pressure systems, (3) coastal seabreeze effect on oxidant levels, (4) relationships between ozone layers aloft and temperature inversions, and (5) ozone transport in the Connecticut River Valley. The field study, which began on July 15, involved research teams from Washington State University (WSU), Battelle, EPA-Research Triangle Park, EPA--LAS VEGAS and EPA---Region I.

In a previous technical report[1] we provided a tabulation of the data collected by WSU during the six week sampling period. The purpose of this manuscript is to provide an analysis of pollutant behavior in relation to sea breeze winds in the metropolitan Boston area and along the Southern Connecticut Coast.

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SECTION I

INTRODUCTION

The sea breeze is a coastal wind that blows from sea to land. It is a localized wind circulation pattern that is caused by the differential thermal properties of land and water. During daylight hours, the land area along a coastline is heated to a higher temperature than the adjacent body of water. This creates a mesoscale low pressure cell over the land surface which causes air movement from the higher pressure sea area toward the lower pressure land area. Above the sea breeze there is often a compensating land-to-sea movement that completes the cycle. Figure 1 provides a diagram of sea breeze characteristics.

The sea breeze is half of the coastal diurnal wind cycle which also includes the oppositely directed nighttime land breeze. At night the sea is generally warmer than the land and consequently the surface wind flow is reversed and a land breeze is observed. The sea and land breeze cycles are important air pollution distribution mechanisms in coastal regions because of the regular diurnal nature of the process and its predominance over synoptic weather patterns in many situations. A well developed sea-land breeze system also provides the opportunity for a recirculation of pollutants since emissions incorporated in the land breeze phase could be returned to the source area after onset of the onshore flow.

As a meteorological phenomenon, the sea breeze has received considerable attention since, on a small scale, it illustrates the principles which are involved in the conversion of the sun's radiant energy to the kinetic energy of atmospheric motions. Allusions to sea breeze type circulations have occurred in writings since the time of Aristotle. A reference to a sea breeze type circulation occurs in Aristotle's writings of approximately 350 B.C. Francis Bacon[2] refered to the sea breeze as turning winds in his essay

about wind in 1664. Much of the early work in this century on sea breeze circulations was performed by the Dutch and Germans, notably van Bemmelen[3] and Koschmieder[4] who reported on land and sea breezes in Batavia and Danzig, respectively.

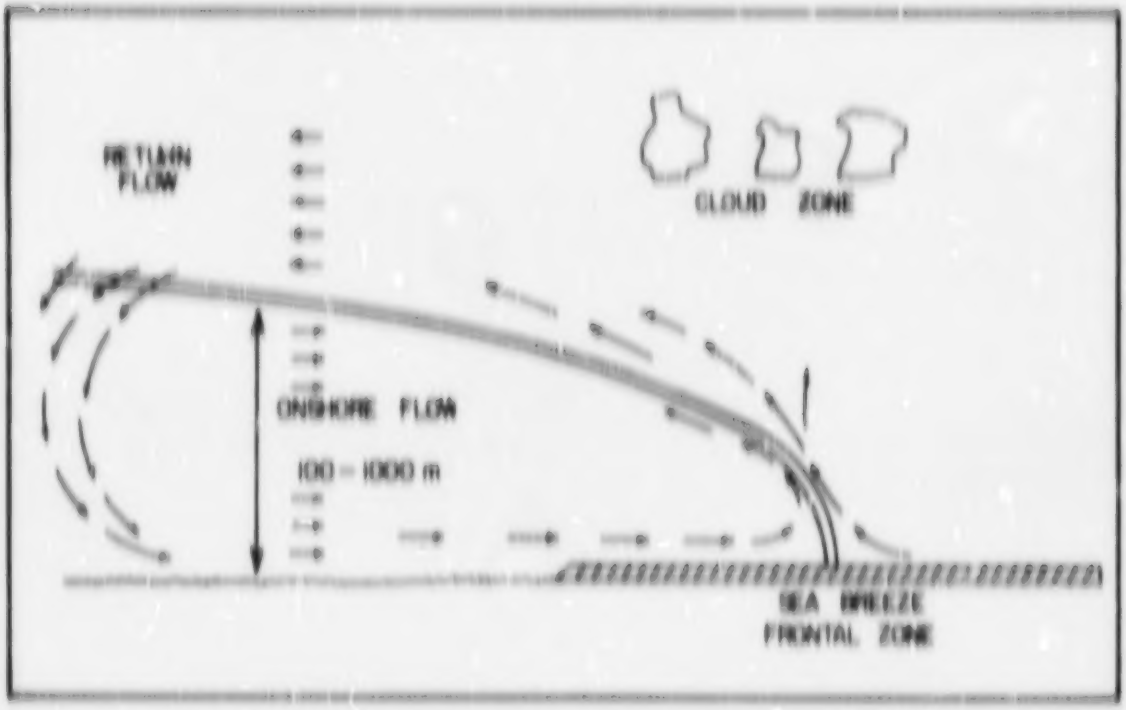

Figure 1. General features of a sea breeze wind system.

In the United States, there have been several studies of sea breeze patterns along the Northeast coastline. Fisher[5] conducted a sea breeze study along the Connecticut coast near Block Island in 1960. Other studies of sea breeze circulations include Frizzola and Fisher[6] in 1963 at New York City; Angell and Pack[7] in 1965 at Atlantic City, New Jersey; and Raynor, Hayes, and Ogden[8] along Long Island. Additional studies have been conducted on the West Coast by Edinger[9] and along the western shore of Lake Michigan by Lyons, Cole

and Olsson.[10,11] Since the sea breeze is dependent on temperature differences between water and land it is not suprising that the occurrence and persistence of a sea breeze are very dependent on meteorological conditions. Strong solar insolation is a necessity as well as daytime temperatures that rise above local water temperatures. Synoptic pressure gradients must be weak since strong gradient winds will overpower the mesoscale sea breeze pattern. A sea breeze is most commonly recorded during the summer months and especially during periods when a high pressure system is centered over the coastal region.

Lyons[12] has pointed out that no two sea breeze conditions are alike, but they all have many similar characteristics. Under ideal conditions (i.e. near zero gradient flow) the surface layer of onshore flow will vary in depth from 100 m to 1000 m, wind speeds are in the range of 10-15 mph and the return flow layer aloft is about twice the thickness of the in-flow layer. Wind speeds in the return flow layer aloft are normally less than 10 mph and consequently are quite easily masked by synoptic winds. Typical areas covered by the sea breeze are from 20 km seaward to 20 km inland.

SECTION 2

SUMMARY AND CONCLUSIONS

Relationships between ambient air quality and sea breeze conditions in southern New England have been examined in this report. Data employed in this analysis were collected during July and August, 1975, by research teams from Battelle (Columbus), EPA-Las Vegas, EPA-Research Triangle Park and Washington State University. Additional useful information was obtained from the National Weather Service and the Massachusetts, Rhode Island and Connecticut State ozone monitoring networks. This report concentrates on sea breeze--pollutant interactions in the Boston area and along the southern Connecticut coast near Groton.

In the Boston area, sea breeze conditions were observed on about 25% of the days from mid-July until the end of August. The onshore flow was generally restricted to a shallow coastal zone. The sea breeze flow seldom penetrated inland as far as Norwood and Bedford (12 miles).

Sea breeze winds can have either a moderating or enhancing effect on ambient ozone levels in the Boston area. It would be very difficult, however, to predict in advance which of these conditions would prevail on any particular day. Probably the most common situation is for the sea breeze to act as a cleansing mechanism for pollutants with lower ozone levels recorded in the region covered by the marine air. This was generally characteristic of the more vigorous sea breeze situations. On occasions when a weak land breeze preceded the onset of a sea breeze, ozone concentrations at coastal stations usually increased quite rapidly at about the time the onshore flow began and then remained at a relatively high level for several hours. Evidence was presented which strongly suggests that on at least two occasions, sea breeze winds contributed to a return of early morning Boston emissions to the city later in the day. This transport cycle appeared to be restricted to a layer

immediately above the surface. Sufficient data was not collected to document recirculation aloft of contaminated air parcels within a sea breeze cell in the Boston area.

In the Groton area of the Connecticut coast a well-developed sea breeze wind pattern was an almost daily occurrence during the 1975 experimental program. High ambient ozone concentrations usually coincided with a sea breeze regime in this area. Aircraft flights over Long Island and the Atlantic Ocean south of the coast showed clearly that the pollutants observed in the coastal areas had been advected over the area by the sea breeze. The pollutants over the ocean were part of the urban plume originating in the New York City - northern New Jersey interstate area.

At Groton there was apparently one situation where the surface sea breeze was linked with a compensating reverse flow aloft forming a potential closed circulation cell. Such a situation could form a mechanism for the recirculation of pollutants over a source area. However, this mechanism is considered to be unimportant in pollutant distributions along the Connecticut coast compared to the advection of the New York City urban plume.

The analysis of the Connecticut sea breeze situations showed that these local wind patterns were much more important than "transport layer" (300-1000 m) winds for explaining the occurrence of high ozone levels in the Groton area.

It is quite evident that sea breeze situations in the Boston area were not as common or as extensive as were observed during the same period along the Connecticut coast. Although we have not carried out a detailed climatological survey of the Boston area, the observed lack of a well developed sea breeze is probably related to the nature of the synoptic weather systems that moved through the area during the study period. Persistent gradient level winds from the westerly quadrant hindered inland penetration of the sea breeze in the Boston area. Along the Connecticut coast, gradient winds from the west tended to cause the sea breeze to veer from a southerly to a more westerly flow, but the sea breeze was not directly opposed as in the Boston area.

Air quality along the Connecticut coast is strongly affected by a well developed sea breeze because this system provides a mechanism for transporting the urban plume from the New York City - New Jersey complex into Connecticut. Sea breeze - pollutant relationships in the Boston area are not as well defined,

however, arrival of the sea breeze at a station usually was associated with a decrease in ozone concentrations. It seems quite apparent that air pollution control strategies for coastal Connecticut must recognize the advection of pollutants by the sea breeze while in the Boston area this represents only a minor feature with little probable impact on control strategies for the urban area.

SECTION 3

EXPERIMENTAL METHODS

Material used for this sea breeze analysis included meteorological and air quality data collected in the New England region by Washington State University, Battelle, EPA-RTP and EPA-Las Vegas during July and August of 1975. Table 1 provides a summary of measurements made by the Washington State University group. The other three research teams monitored most of these same parameters. A detailed description of the program design, location of monitoring sites and experimental techniques has been provided elsewhere[1].

Two other data sources provided valuable information: 1) National Weather Service wind data recorded at coastal airports in New England; and 2) Massachusetts, Rhode Island and Connecticut surface ozone data obtained from state monitoring stations.

TABLE 1. WSU GROUND AND AIRCRAFT MEASUREMENTS

Ground-Level Measurements

Ozone	Wind Speed
Oxides of Nitrogen	Wind Direction
Total Hydrocarbon	Turbulence
Methane	Dew Point
Carbon Monoxide	Solar Radiation
Individual C_2-C_6 Hc	Temperature
Halocarbons	Vertical Temperature Discontinuity (Acoustic Radar)

Aircraft Measurements

Ozone
Condensation Nuclei
Visual Range (Nephelometer)
Temperature
Relative Humidity
Navigational Parameters (VOR, DME, Altitude, etc.)
Bag/Can Samples (Hydrocarbons, Halocarbons, NO_x, etc.)

SECTION 4

RESULTS AND DISCUSSION

SEA BREEZE EFFECTS IN THE GREATER BOSTON AREA

A careful analysis has been made of the meteorological and analytical data from the study period to determine the characteristics and frequency of sea breeze conditions in the Boston area. The presence of a sea breeze was determined primarily from wind data at Logan International Airport. The close proximity of the airport to the ocean permitted early detection of a wind shift characteristic of an onshore flow. Wind data from inland stations was used to document inland penetration of the sea breeze. Figure 2 provides the indentity of surface wind stations used in this analysis. Moisture content of the air (dew point) and temperature were also used as an indicator of onshore flow. A rise in dew point and decrease in temperature were normally observed as the cooler and more moist marine air moved inland.

For example, on August 2, 1975 the sea breeze wind shift occurred at 1000 at Logan Airport. Temperature and dew point data for this day are listed in Table 2. Beginning at 0600, the temperature began a normal daily rise. Between 0900 and 1000 the temperature decreased two degrees while the dew point increased two degrees as the cooler and more moist marine air began to move onshore. These meteorological changes then reversed as the sea breeze died out at approximately 1700. In succeeding paragraphs we will point out various general characteristics of the Boston area sea breeze. Specific examples which illustrate how the sea breeze affects ambient pollutant levels will also be provided.

General Meteorological Features. Assessment of the wind data from Logan International Airport and the surrounding wind stations indicates that the sea breeze was not a frequent occurance in the Boston area. Over the six week

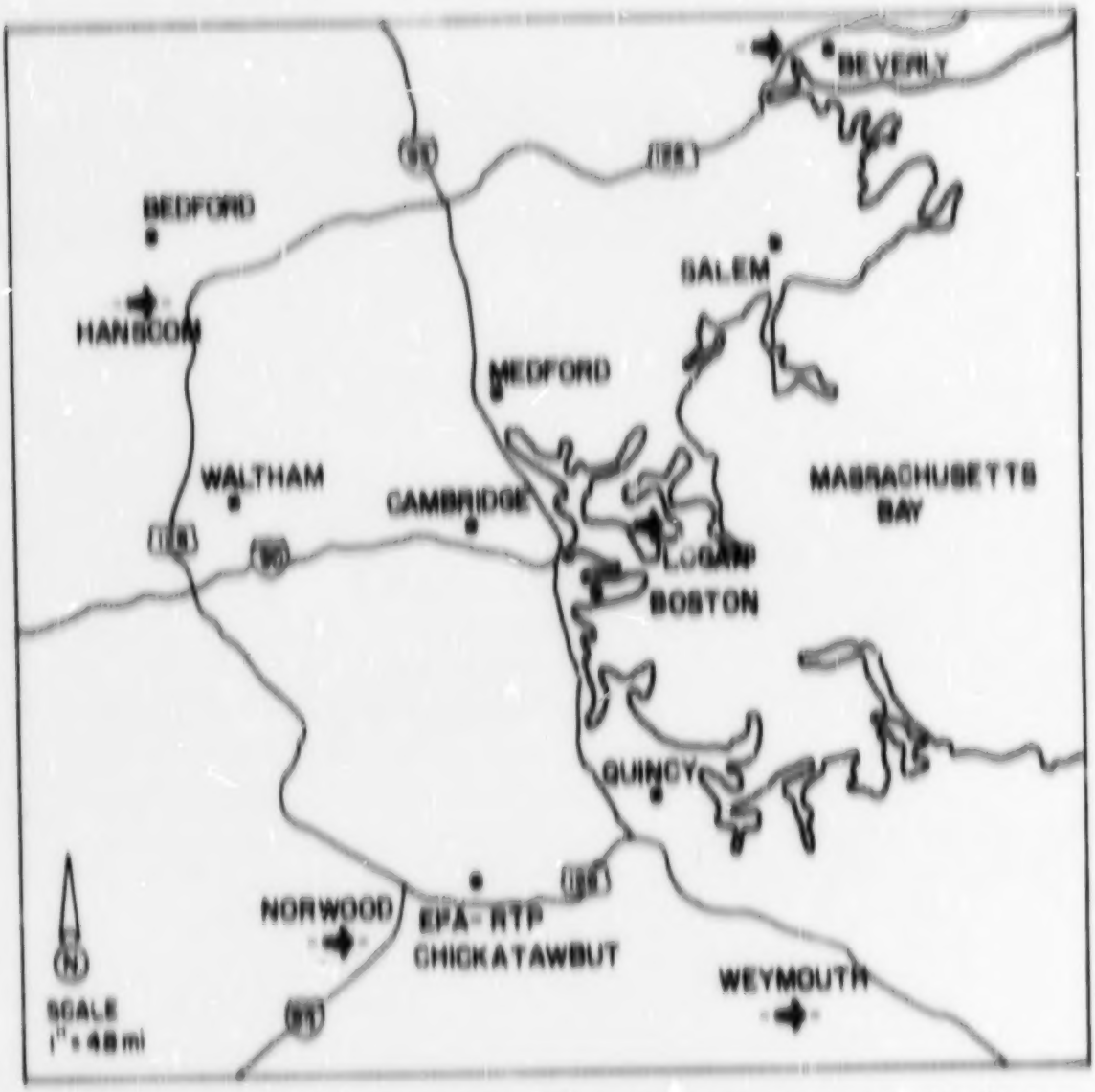

Figure 2. Location of surface wind (-➡-) and ozone stations in the Boston area.

TABLE 2. METEOROLOGICAL MEASUREMENTS AT LOGAN AIRPORT ON AUGUST 2, 1975.

Time	Wind Direction deg	Wind Speed mph	Temp. deg	Dew Point deg
0400	320	9	84	70
0500	320	10	84	70
0600	320	10	86	70
0700	320	9	88	70
0800	330	7	91	70
0900	350	7	94	69
1000	130	4	92	71
1100	140	4	93	71
1200	140	5	97	70
1300	160	5	100	70
1400	130	5	101	69
1500	120	7	98	68
1600	130	6	96	68
1700	100	7	98	66
1800	290	8	99	65
1900	280	10	98	66

sampling period only ten days can be readily associated with a sea breeze. Table 3 lists Logan Airport surface wind data between the hours of 0700 and 2000 for the period July 15 - August 24. The tabulated data show the direction from which the wind is blowing in 10° sectors and the wind speed in knots, e.g. 0905 means wind from 90° at 5 knots. The days of July 22, 27 and August 1, 2, 9, 11, 12, 13, 16, 17 exhibit a wind shift that can be ascribed to the onset of a sea breeze. These periods are blocked in Table 3 for easy recognition.

On sea breeze days the shift from offshore to onshore flow normally occurred about 0900 at Logan International Airport. A return to westerly flow was always observed during the evening hours. It should be pointed out that all the general features mentioned thus far apply mainly to the immediate coastline area around Logan Airport. Quite often the marine air moving as a sea breeze front did not penetrate far enough inland to be recorded at more westerly wind stations. Only on three of the ten days was a sea breeze wind shift recorded at Bedford (Hanscomb Airport), 12 miles inland.

The relative infrequency of a coastal sea breeze regime in this area is probably due to an interaction between the onshore sea breeze flow and the generally offshore flow of the gradient or synoptic pattern winds. Longer term

TABLE 3. SURFACE winds AT LISBON INTERNATIONAL AIRPORT

Time	Date												
	7/15	7/16	7/17	7/18	7/19	7/20	7/21	7/22	7/23	7/24	7/25	7/26	7/27
0700	2110	1809	2411	2506	2513	2308	2527	3010	2809	2309	2211	2510	1202
0800	2613	2312	2514	2509	2513	2208	2513	3208	2908	2308	2213	3011	1404
0900	2815	2310	2612	2709	2416	2209	2611	3207	2706	2209	2213	3013	1405
1000	2817	2510	2512	2510	2417	2311	2411	3305	2509	1908	2412	3312	1705
1100	2215	2510	2611	2505	2516	2211	2710	2403	2408	2311	2413	3412	1907
1200	2214	2612	2311	2605	2417	2210	2710	2604	2210	2415	2413	2909	1810
1300	2314	2412	2412	2510	2415	2413	2911	1009	2508	2315	2409	3013	1511
1400	2415	2612	2213	2411	2419	2410	2413	1009	2412	1913	2212	2907	1113
1500	2112	2812	2314	2310	2318	2010	2516	1107	2410	1814	2413	3108	1113
1600	2314	1914	2515	2410	2216	2412	2714	1007	2612	1916	2614	3107	1113
1700	2211	2014	2314	1909	2214	2010	2810	1208	2412	1918	2313	2906	1214
1800	2012	1911	2215	1807	1914	2216	2608	1305	2316	2015	2312	3310	1206
1900	1909	2210	2211	2311	2516	1909	2408	1204	2411	2075	2212	3407	1209
2000	2010	2313	2110	2108	2113	2013	2406	1205	2309	2014	3413	2205	1205
2100	2109	2212	2313	2313	1914	2010	2508	1202	2307	1913	2710	1607	1104
2200	2209	2212	2412	2413	2215	2208	2506	1904	2407	1908	3113	1806	1703

TABLE 3 (cont.)

Time	Date												
	7/29	7/29	7/30	7/31	8/1	8/2	8/3	8/4	8/5	8/6	8/7	8/8	8/9
0700	2404	2910	2704	2901	2234	3209	3604	1057	2103	3532	0404	2257	CAL*
0800	2307	2911	3006	2909	0704	3307	3505	0705	1408	0405	0515	1308	2906
0900	2413	3012	2805	2909	1405	3507	0408	0807	1602	0411	0406	0402	2906
1000	2413	3308	2904	2710	1305	1304	0408	3608	3505	0412	0407	0310	3257
1100	2513	3410	2906	2709	1406	1405	0709	0706	1306	0709	0405	0404	3257
1200	2413	3511	2907	2605	1607	1405	0412	1010	1108	0611	0409	0406	3105
1300	2304	3012	1909	2911	1307	1135	0411	1010	1107	0210	0406	1516	1307
1400	2404	2911	2212	3010	1306	1305	0312	0910	1111	0707	0205	0513	1407
1500	2909	2910	2412	2710	1405	1257	0513	1110	1109	0607	0212	0108	1405
1600	2410	3206	2707	3112	2805	1306	0414	1305	1107	0707	0211	3507	1307
1700	2512	3110	2910	3110	2911	0807	0311	2809	0907	0907	0111	3615	2204
1800	2410	3011	2513	2910	2911	2906	0205	0908	0705	0706	3611	3507	3006
1900	2707	3008	2509	3307	2911	2910	0308	1107	0905	0507	3409	0105	2908
2000	2607	2704	2505	3205	2909	3008	0204	1205	1204	0408	3409	3507	3506
2100	2705	3005	2306	3016	2510	2905	0607	1203	3503	0608	3408	3506	2906
2200	2406	3305	2308	2905	3009	2905	0607	1304	1001	1305	3509	3216	3907

TABLE 3 (cont.)

Time	Date												
	8/10	8/11	8/12	8/13	8/14	8/15	8/16	8/17	8/18	8/19	8/20	8/21	8/22
0700	2527	2502	3109	3204	2510	3310	0234	1404	2605	3111	3109	2605	2512
0800	2706	CALM	3103	3003	2506	3310	0104	1305	2707	3210	3109	3006	2514
0900	2908	1304	0402	0405	2710	3405	1004	1104	2907	3110	3108	2505	2514
1000	2708	1304	0702	0604	2407	3207	0604	0905	3010	3110	3308	2605	2715
1100	3106	0703	0405	0405	2909	3010	0203	1104	2506	2910	3309	2310	2715
1200	2612	1208	0510	0510	2711	2904	1305	1304	3010	2707	3108	3504	2715
1300	3006	1110	1107	0210	2913	2711	1105	0604	3072	2812	2910	2007	2615
1400	3216	1110	1308	0205	2719	3006	0405	1206	2913	2910	3010	2611	3316
1500	2710	1304	1206	1110	2715	3409	1008	0504	2814	2610	3212	2213	3613
1600	3012	1307	1106	1402	2505	3310	1308	1107	2914	2611	3013	2416	3414
1700	2940	2408	0405	0608	2912	3210	1307	1105	2913	3010	3110	2313	3415
1800	2610	2707	1205	0707	2911	3209	1208	1104	2713	2810	3117	2511	3416
1900	2510	2508	0705	2008	2910	3107	1508	0207	3111	2306	2908	2508	3212
2000	2606	2510	2105	1404	2910	2905	1107	0906	2912	2507	2906	2307	3210
2100	2504	2404	3105	2205	2911	2506	2108	1907	2911	2506	2806	2309	3210
2200	3004	2407	1906	2307	2910	3404	2205	1504	2912	2906	2905	2308	3209

wind frequency data for Boston do not show that winds from an easterly quadrant are a dominant aspect of the climatology. Increased surface roughness and convective activity associated with the Boston metropolitan area probably have little affect on the frequency of sea breeze occurrence. If anything, these urban features might tend to increase the influence of the gradient wind on surface layer flow.

Evidence of a closed cell circulation pattern, i.e. westerly return flow aloft over the easterly sea breeze is lacking for the Boston sea breeze area. Detailed wind trajectory data were not obtained and consequently recirculation information must be gleaned from other less informative sources. The amount of upper level wind data in the Boston area is very limited on the afternoons when sea breeze conditions prevailed. Only on one day, August 13, was a pilot balloon released that provided adequate wind aloft data. Table 4 shows that there was a reversal in wind direction over Boston during the sea breeze period on August 11. In a classical sense this constitutes a return flow and implies a circular wind pattern. However, this intrepretation and more importantly the possibility of recirculation of pollutants is complicated by the fact that gradient winds were from the west. Consequentiy it is impossible to determine what part, if any, of this westerly flow aloft results from sea breeze recirculation. A more detailed discussion of this problem will be provided in the next section.

General Pollutant Features. The onset of a sea breeze can result in either an improvement or a degradation in air quality depending on pollutant levels in the air mass over the water. If the pollutant burden is high a deterioration in air quality at onshore locations will be recorded as the sea breeze front moves inland. On the other hand if the marine air is clean, air quality will improve. Pollutant information in the Boston area that can be correlated with sea breeze conditions is limited mostly to ozone data since the onshore flow seldom reached the EPA-RTP monitoring station at Chickatawbut Hill where many other gaseous pollutants were measured. In order to illustrate relationships between the sea breeze and ambient ozone concentrations in the Boston area, pollutant patterns on six sea breeze days will be discussed. July 27, August 1, 2, 11, 12 and 13 were chosen for this purpose. The location of ozone monitoring stations mentioned in the subsequent discussion are shown in Figure 1.

TABLE 4. PIBAL DATA FROM BOSTON, MASSACHUSETTS AT 1309 ON AUGUST 13, 1975.

Height (ft)	Wind Direction (degrees)	Wind Speed (mph)
1000	114	8
2000	181	5
3000	243	9
4000	258	9
5000	273	9

July 27, 1975 - Weather observations at Boston's Logan Airport showed a wind shift to onshore flow by about 0900. Inland at Bedford the wind began to change about 1100 but the sea breeze system was not clearly established at this station until early afternoon. The easterly flow across the region persisted until about 2100 at most locations around Boston. Table 5 lists hourly ozone concentrations at Salem, Medford, Cambridge and Quincy on July 27. The blocked time periods on each day mark the beginning and end of the sea breeze period at Logan International Airport. Ozone patterns at the four coastal stations do not exhibit unusual behavior on this day. With the exception of Cambridge, ozone concentrations peaked about 1300 with a normal diurnal rise and fall before and after the peak. Cambridge peaked somewhat earlier which could possibly mean that the sea breeze provided a cleansing effect at that station. Figures 3 and 4 show regional ozone and wind data at 1500 on the 27th. The ozone pattern in Figure 3 supports a cleansing influence by the sea breeze since stations in the coastal zone generally exhibit lower concentrations than the more inland monitoring sites. The general ozone pattern in the Boston area on July 27 is consistent with a southeast to northwest sea breeze flow that brought cleaner air over the area and carried an "urban plume" to the northwest. Aircraft data collected in an arc around Boston (Figure 5) showed ozone values somewhat higher in the sector northwest of Boston, 70-79 ppb, compared to 50-60 ppb in the southeast sector.

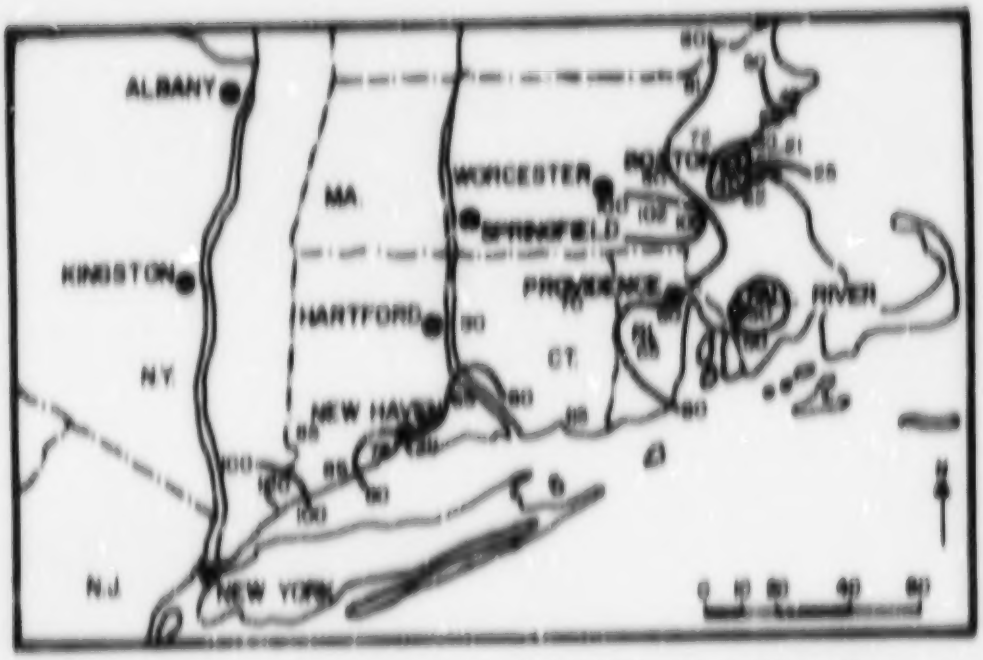

Figure 3. Surface ozone concentrations (ppb) in southern New England at 1500 on July 27, 1975.

Figure 4. Surface winds in southern New England at 1500 on July 27, 1975.

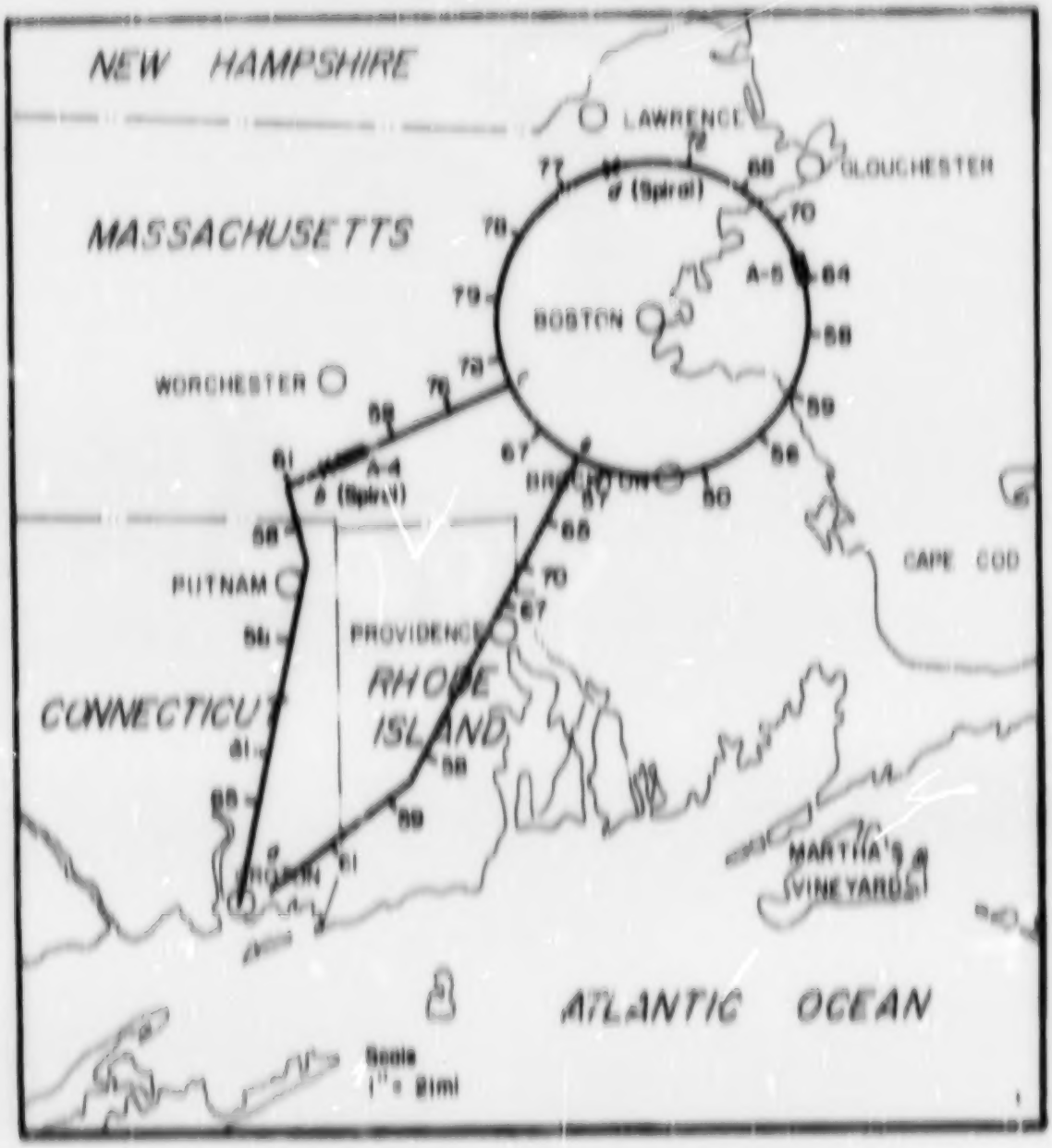

Figure 5. WSU aircraft flight path on the afternoon (1450-1755) of July 27, 1976, with ozone concentrations (ppb) marked at specific points along the route.

August 1 - A very interesting ozone pattern existed in the Boston area on this day. Air quality at Salem appears to have been adversely affected by the sea breeze. As shown in Table 5 the ozone concentration jumped from 38 to 70 ppb at the beginning of the sea breeze period. It remained high during the late morning and early afternoon hours and then decreased dramatically from 92 to 29 ppb between 1400 and 1500. This is the same time sea breeze winds dissipated at Logan International. Thus high ozone concentrations at Salem on August 1 correlate very closely with the sea breeze period. Ozone behavior at the Medford station resembled that at Salem. The sharp drop in ozone occurred one hour earlier at Medford which is consistent with an earlier fall-off in the onshore flow at a more inland station. The two more southerly stations, Cambridge and Quincy, exhibited an ozone pattern that differed from that just described for Salem and Medford. They showed a large increase at the start of the sea breeze period but then air quality improved until the on-shore flow ceased. A second ozone maximum followed immediately after the fall-off in onshore flow at each of these stations. The second ozone peak occurred one hour earlier at the more westerly Cambridge station.

These observations are consistent with the observed wind pattern and its likely interaction with the Boston urban area pollutants. On August 1 the winds were northwest and north until about 0700, when they began to veer through east at about 0800 and took up a typical sea breeze direction of south-east at 0900. Wind speeds were generally 5 knots or less from midnight on. This pattern would have initially moved urban-area pollutants out over Boston Harbor and nearby coastal ocean areas and then back over the land areas. The ozone levels were highest in the Medford area, the station nearest Boston. There is some indication in the Logan Airport dew point data that the air parcels contained in the initial sea breeze push, between 0900 and 1000, had not been over the ocean areas very long because the dew point dropped 2 to 3°F with the wind shift to the southeast sea breeze. The easterly sea breeze flow was apparently limited to a narrow strip along the coast and was not observed inland at Bedford where the midday wind was westerly, the direction of the general gradient flow. To the south of Boston at South Weymouth, the sea breeze was from the northeast at 2 to 3 knots and was limited to a 2 to 3 hour period around 1100. From 1300 to 1700 winds were westerly.

Ozone concentration had apparently increased rapidly in the air mass after sunrise while it was over the water. This resulted in the large ozone

jump observed as the marine air moved inland. The southeasterly sea breeze flow rusulted in greater fumigation of the most northerly stations and thus ozone levels remained high during the entire sea breeze period at Medford and Salem.

As the sea breeze flow broke down during the midafternoon hours, northwestly gradient winds once again prevailed and moved the polluted air mass lying to the northwest of Boston back across the city. Consequently, high ozone levels were recorded at the two more southerly stations following dissipation of the onshore flow. This then represents a case in which a combination of gradient flow and sea breeze winds resulted in the transport of urban emissions across the city twice in one day. It is also a situation where there were enough pollutants in the land breeze cycle so that high pollutant concentrations were recorded during the initial hours of the sea breeze.

August 2 - Ozone patterns on this day don't appear to reflect a sea breeze influence. Winds at Logan International show a sea breeze shift (Table 3); however, it is doubtful that the onshore flow penetrated inland to any of the ozone monitoring stations. Winds at Beverly and Chickatawbut Hill were generally northwesterly and varied between 300 and 360° throughout the day. The ozone pattern shown in Table 5 is consistent with a northwesterly gradient flow. Quincy and Cambridge exhibited a higher ozone peak than the more upwind stations near Medford and Salem. Flights conducted by WSU on this day verify the southeasterly movement of the Boston air mass. As can be seen in Figures 6 and 7, highest ozone values were recorded in the Brockton area about noon and then out over Cape Cod Bay during the evening hours. The one wind station besides Logan which exhibited a sea breeze shift on August 2 was South Weymouth, where winds were out of the east between 1700 and 1900. Ozone levels at Quincy (near South Weymouth) showed a dramatic drop, from 102 to 11 ppb during this two hour period. While this is a time of day when ozone levels are normally falling, this rapid of a decrease is unusual. It seems that the marine air flowing onshore during this two-hour period must have contained a very low ozone burden and consequently, helped to lower ambient concentrations at Quincy.

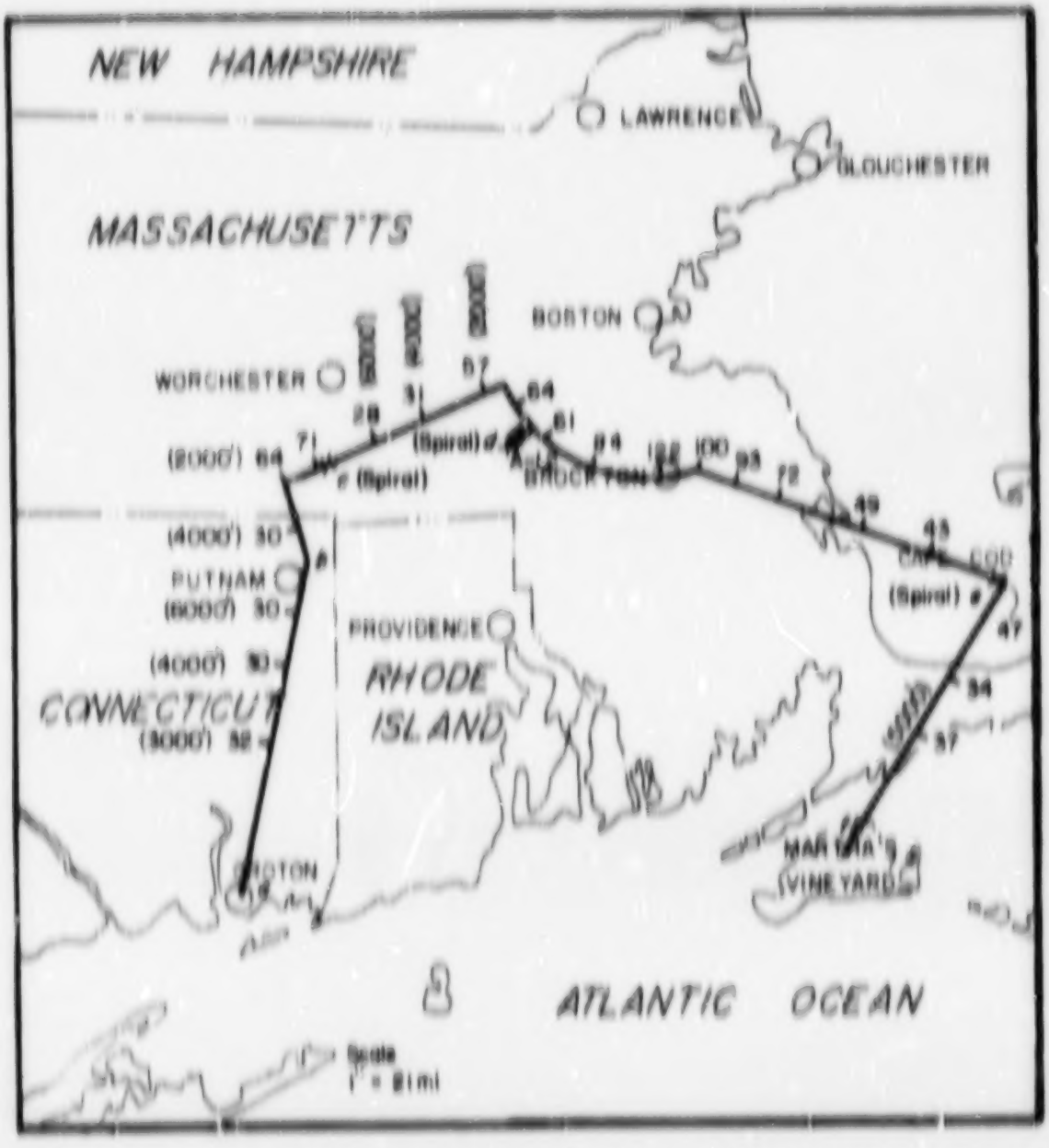

Figure 4. WSU aircraft flight path on the afternoon (1200 to 1440) of August 2, 1975, with ozone concentrations (ppb) marked at specific points along the route.

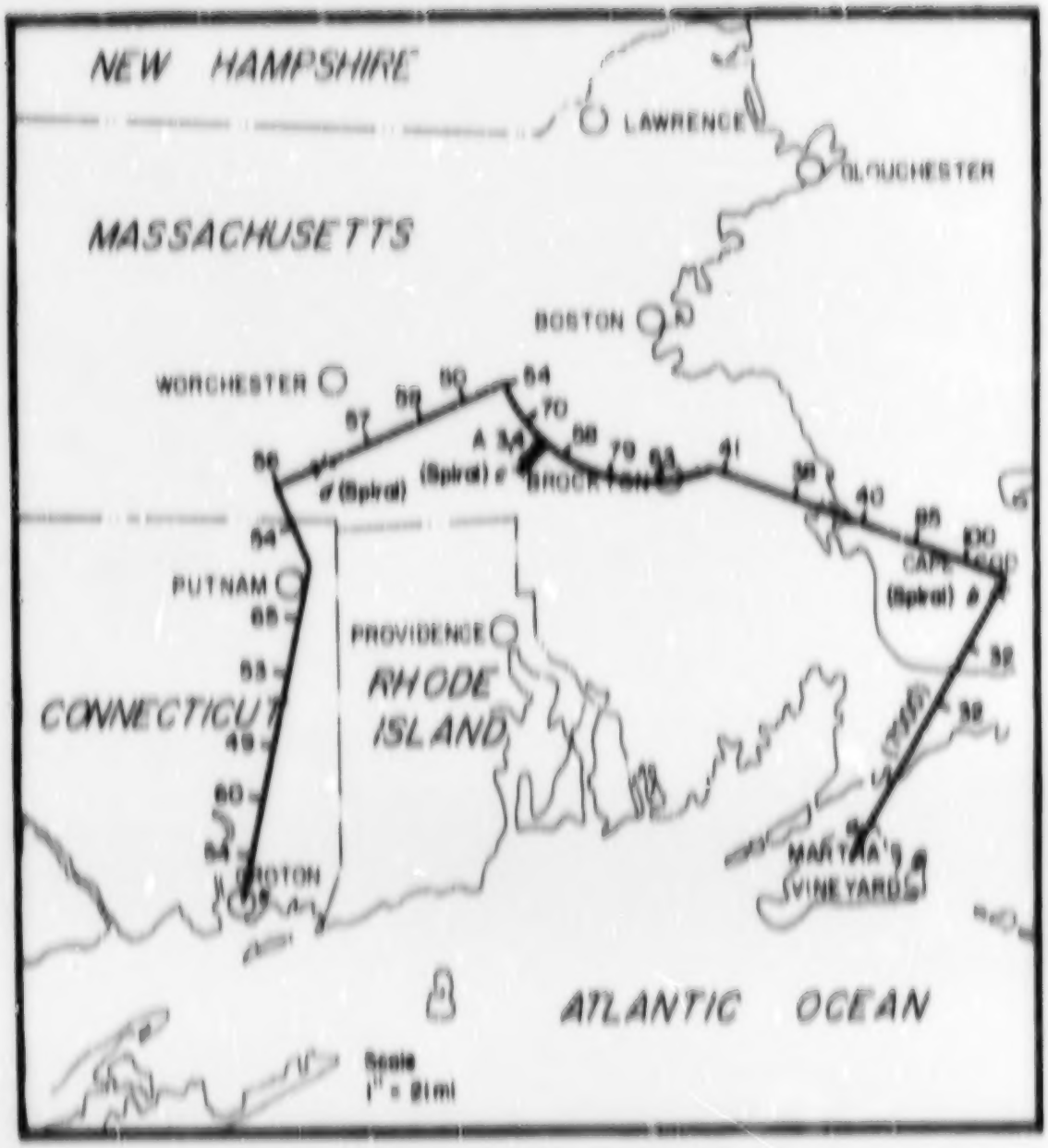

Figure 7. WSU flight path on the evening (2035 to 2320) of August 2, 1975, with ozone concentrations (ppb) marked at specific points along the route.

August 11 - Judging from the ozone data in Table 5 and the wind data from Table 3, the beginning of the sea breeze, about 0900 at Logan Airport, corresponded to a degradation in air quality at near-by Medford. The maximum ozone concentration at Medford occurred at 1400. The ozone pattern at Quincy, to the south, showed a significant increase between 0900 and 1000, just after the start of the sea breeze at Logan Airport, and a maximum concentration of 142 ppb at 1300. It appears that photochemical production of ozone began about the time the sea breeze commenced and that ozone accumulated rapidly between 0900 and 1000 in air that moved with the sea breeze. The pollutants that were involved in this early O_3 formation had sources within a few miles of the monitoring station because winds were very weak. Cambridge experienced an initial ozone increase as the onshore flow moved through, then a decrease as cleaner marine air fumigated the station. By 1400 the sea breeze began to dissipate; and with the return to offshore flow, the more highly polluted inland air mass was recycled through the downtown area. Ozone levels increased between 1500 and 1800 at the Cambridge station. The wind data from inland stations at Bedford and South Weymouth did not show any sea breeze effect, so it is concluded that the event was restricted to a narrow coastal zone.

August 11 is the only sea breeze day in which detailed hydrocarbon data is available in the downtown Boston area. EPA-RTP conducted a diurnal study of C_2-C_{10} hydrocarbons at the JFK Building on this day. The diurnal hydrocarbon changes shown in Table 6 support the sea breeze analysis just proposed. Hydrocarbon levels were high during the 0900 to 1200 period as the onshore flow began, then decreased as the polluted air mass moved farther inland and increased once again during the 1500 to 1800 period as the offshore flow returned.

August 12 - The onshore flow penetrated farther inland on this day than on most other occasions. Easterly wind shifts were recorded at both Norwood and Bedford during the early afternoon hours. Since the onshore flow moved well past the four coastal stations it is difficult to recognize any discernible patterns from the ozone data provided in Table 5. If anything it appears that the sea breeze, once again, served to lower afternoon ozone maxima at Salem, Medford, Cambridge and Quincy on August 12. This hypothesis is based on a comparison of ozone data recorded on August 10 and 12. A sea breeze did not materialize on the 10th but otherwise meteorological conditions (wind

TABLE 6. HYDROCARBON CONCENTRATIONS (ppbC) MEASURED AT JFK BUILDING ON AUGUST 11, 1975

Hydrocarbon	TIME			
	0600 0900	0900 1200	1200 1500	1500 1800
Acetylene	7.8	34.8	14.1	16.8
propane	8.1	17.0	7.7	12.8
propene	1.5	8.6	3.6	6.0
i-butane	6.8	31.6	10.2	22.4
n-butane	15.9	90.5	28.6	27.0
i-pentane	-	102.6	30.9	31.1
n-pentane	-	53.3	16.5	16.9
toluene	31.2	76.8	23.9	35.1
ethylbenzene	7.0	12.6	4.0	6.0
xylenes	52.3	66.2	23.7	36.9

TABLE 7. OZONE AND WIND DATA AT EPA-RTP CHICKATAWBUT HILL SITE ON AUGUST 10, 12 AND 13, 1975

	8/10			8/12			8/13		
TIME	O_3 ppb	WD Deg	WS mph	O_3 ppb	WD Deg	WS mph	O_3 ppb	WD Deg	WS mph
0100	44	290	7	58	300	4	6	300	1
0200	57	290	7	65	350	5	9	320	3
0300	55	290	7	63	340	4	13	330	4
0400	54	290	7	61	300	3	7	340	4
0500	51	280	6	47	300	3	6	340	6
0600	45	290	6	51	310	4	9	350	6
0700	41	300	7	46	320	6	12	350	4
0800	44	300	7	29	330	4	15	350	3
0900	47	300	5	26	340	5	14	350	3
1000	55	300	5	45	360	4	24	60	7
1100	70	300	4	59	80	3	50	20	3
1200	86	300	3	78	90	2	68	90	2
1300	99	300	3	104	90	3	76	360	1
1400	98	300	5	97	80	5	88	240	3
1500	96	300	5	98	80	5	108	270	3
1600	99	310	5	102	80	3	99	260	4
1700	90	300	4	97	80	4	77	270	3
1800	85	300	5	74	90	3	62	240	3
1900	73	270	3	57	120	2	63	230	6
2000	68	280	8	46	150	2	63	220	6
2100	63	300	5	38	330	3	44	240	5
2200	57	300	5	55	330	1	49	240	7
2300	52	290	4	61	320	3	66	250	9
2400	47	300	5	39	360	3	72	220	10

speed, temperature, solar insolation) were very similar on the two days. The afternoon ozone peak at Cambridge on the 10th was 98 ppb compared to less that 50 ppb on the 12th. At Quincy the recorded values were 124 ppb on the 10th and 79 ppb on the 12th. Thus the afternoon hourly ozone maximum was at least 40 ppb lower at both of these stations on the sea breeze day.

August 12 was one of the few days when a sea breeze wind shift was recorded at the EPA-RTP Chickatawbut Hill site. Wind and ozone data recorded on August 12 at Chickatawbut Hill are listed in Table 7. Data for the non-sea breeze day August 10 are also shown in Table 7. It is obvious that there is very little difference in the ozone pattern on these two days. During the period of easterly winds on August 12 ambient ozone concentrations reached approximately 100 ppb. During the same time period on August 10 ozone levels were in the 100 ppb range. Consequently it appears that the sea breeze had no noticeable effect on ambient ozone levels at Chickatawbut Hill on August 12.

August 13 - Throughout the early morning hours of August 13th northwesterly gradient winds moved Boston area emissions to the southeast. This plume began to be diverted to the west following development of onshore sea breeze winds at about 0900. Thus, the region to the south of Boston experienced the greatest pollutant impact. Table 7 shows that the easterly flow was monitored at Chickatawbut Hill between the hours of 1000 and 1200. Fumigation at the Chickatawbut Hill site was manifested by a large increase in fluorocarbon-11 concentrations during this time period. Prior to the wind shift fluorocarbon-11 levels were approximately 300 ppt. By 0920 the ambient concentration had risen to 734 ppt and at 1000 to a peak of 906 ppt. The concentration then began to drop and was generally less than 300 ppt during the rest of the day. Other primary pollutants showed a similar jump. The NO_x value of 65 ppb (NO = 41; NO_2 = 24) at 1000 was the highest recorded on August 13.

As can be seen in Table 7 ozone remained relatively low during the sea breeze period at Chickatawbut Hill but increased rapidly between 1200 and 1500. Figure 8 shows that at 1400 a region of high ozone existed south of Boston extending from Quincy to Waltham. During the early afternoon hours on August 13 a change in the regional synoptic wind flow pattern occurred. Whereas on preceding days gradient winds had been from the northwest they now shifted to the southwest (Table 7). With the change to southwesterly flow the polluted air mass that existed south and west of Boston began to move in a northeasterly

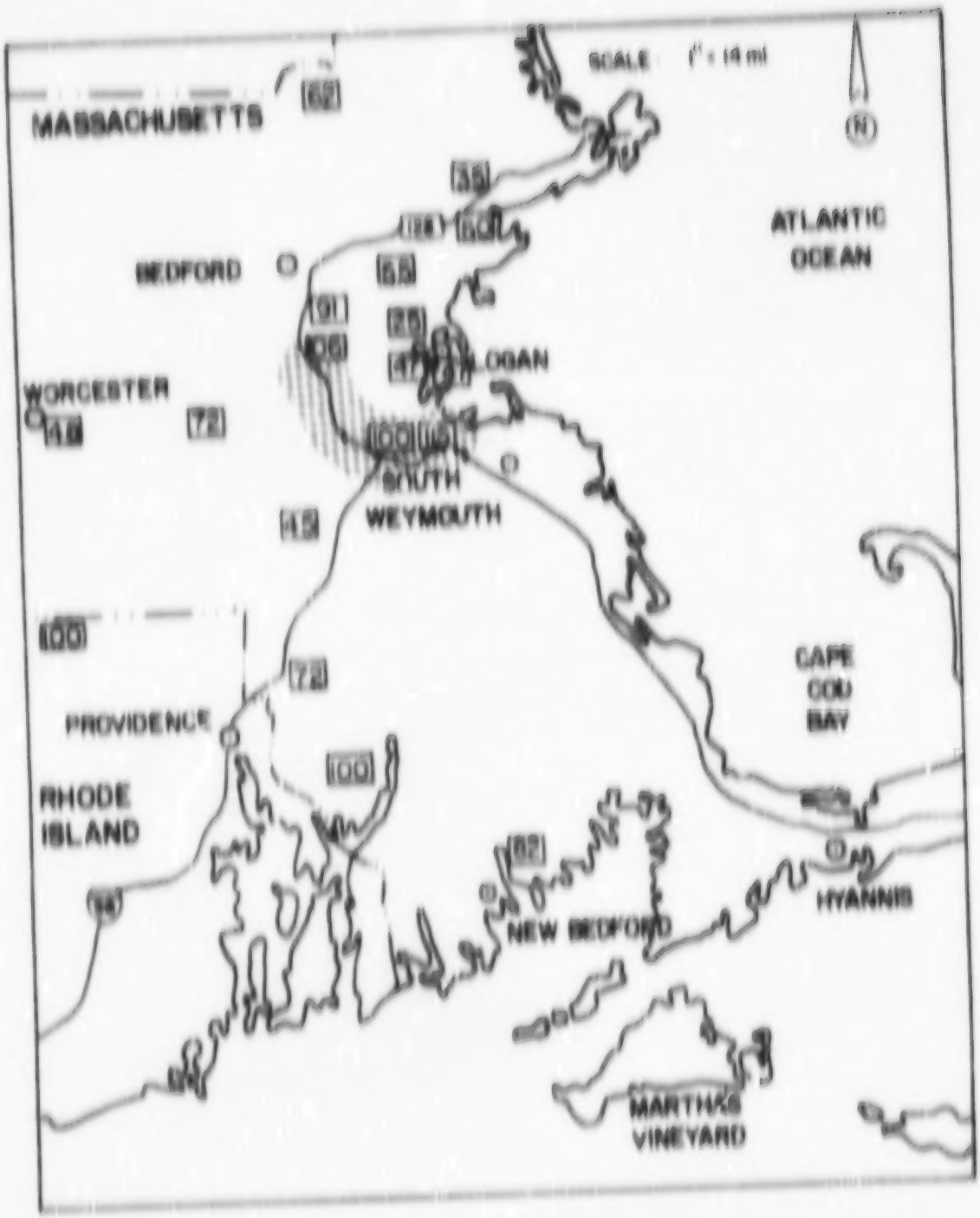

Figure 8. Surface ozone concentrations (ppb) in eastern Massachusetts at 1400 on August 13, 1975.

direction across the city. This is reflected in the increase in ozone concentrations (25 ppb to 59 ppb) at Cambridge between 1400 and 1800 (Table 5). Thus it is very likely that on August 13 emissions that left Boston during the morning hours contributed to the ozone build-up south and west of the city during the early afternoon and also caused an ozone peak during the early evening hours in downtown Boston. A second late ozone peak near 2400 on August 13 was not related to the Boston area sea breeze. The midnight peak clearly resulted from long distant transport of ozone from source areas to the southwest.

It is obvious from the preceding analysis that it is very difficult to make generalizations concerning sea breeze ozone relationships in the Boston area. An even more troublesome task would be to try to predict in advance the impact sea breeze winds would have on pollutant levels at various locations. Probably more often that not, the sea breeze provided a cleaning effect with ozone levels being lower than during comparable non-sea breeze periods. However, even at the stations closest to the coastline examples can be cited that jeopardize this premise. The pollutant impact depends not only on sea breeze variables but also on gradient wind flow before and after the period of onshore winds.

Data obtained on August 11 and 13 suggested that sea breeze winds contributed to a recycling of Boston emissions, or at least to a bimodal distribution of concentration. In both of these cases the pollutant transfer was described in terms of air mass movement at the surface with no mention of recirculation aloft of contaminated air parcels within a sea breeze cell. In theory a sea breeze recirculation cell aloft could provide a mechanism whereby an air parcel that originated in the Boston urban area could be carried inland, lifted up and sent seaward in the return flow aloft. The air parcel could then subside over the water and be carried inland again. During this transport process photochemically induced reactions could produce secondary pollutants such as ozone in the contaminated air parcel. Upon its return to the Boston area elevated ozone levels would be recorded.

As indicated previously, August 13 was the only sea breeze day on which a westerly or possible return flow aloft was observed (Table 4). On this day ozone concentrations were increasing at the Cambridge stations during the end of the sea breeze period a fact that could possibly be ascribed to sea breeze

recirculation. However, the alternate late peak explanation provided in the August 13 analysis section seems more reasonable. Better documentation exists for fumigation at Cambridge from an inland direction rather than an easterly direction required of a closed cell sea breeze recirculation. Sufficient data has not been collected in the Boston area to document recirculation aloft of contaminated air parcels within a sea breeze cell.

SEA BREEZE EFFECTS IN THE GROTON, CONNECTICUT AREA

The relationship between seabreeze conditions and pollutant levels in the Groton area (Figure 9) is considerably different than that described earlier for the Boston area. Oxidant precursor emissions are much lower in the southeast sector of Connecticut than in the Greater Boston area. The annual tonnage of hydrocarbons and oxides of nitrogen is about a factor of 10 lower in the Groton area.[13] This means that recycling of pollutants in a sea breeze circulation pattern would have less of an impact along the southern Connecticut coast. However, in this region another important factor must be considered. The New York City - New Jersey urban and industrial complex is approximately 80 miles to the west which during the summer months is generally in an upwind direction. New York emissions transported in an easterly direction definitely have a large impact along the Connecticut coast. High secondary pollutant levels were commonly observed in this transported air mass probably due in part to the fact that a majority of the trajectory was over water where ozone scavenging sources are minimal. With transport wind speeds of 10-20 mph the polluted air mass from New York had ample time to undergo photochemical transformation before reaching coastal areas around Groton. As will be shown, the sea breeze wind played a major role in moving polluted air parcels from over Long Island Sound and the Atlantic onshore along the Connecticut coast.

The sea breeze-pollutant interaction in this region of New England is very similar to the situation along the western shore of Lake Michigan. The work of Lyons and Cole[11] has shown that pollutants emitted in the Chicago-Gary region are transported in a northly direction over Lake Michigan. Following onset of a lake breeze this contaminated air mass fumigates the Wisconsin coastline and results in severe air quality degradation. Highest ozone concentrations were normally recorded between 60 and 90 miles north of the

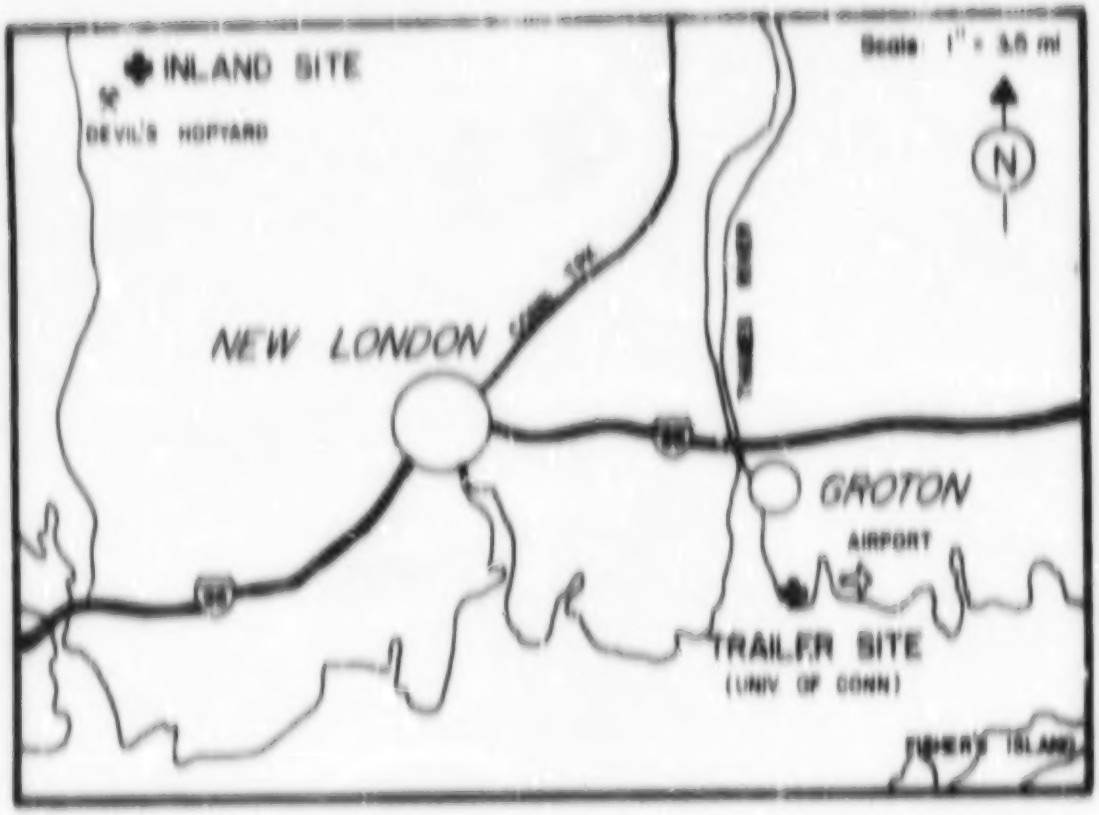

Figure 9. Map showing Groton study area.

Chicago source area. Along the Connecticut coastline wind directions are different; however the transport mechanism is exactly the same. In the next sections it will be shown that high ozone concentrations in the Groton area can nearly always be traced to air masses originating in the New York - New Jersey complex.

One important result from this detailed assessment of local winds along the Connecticut coast has been a recognition that air mass trajectories based on winds in the 300-1000 m "transport layer" differ considerably from trajectories that take sea breeze winds into account. A review of calculated "transport layer" trajectories[14] indicates that pollutant fumigation occurred predominately from the northwest sector. However, ambient measurements clearly show that ozone transport was the result of a sea breeze system moving polluted air from the southwest. Thus, in most cases the source of the pollutant plume

was the New York City area and not the area of Connecticut that was northwest of Groton. The establishment of this important role of the low level, local wind patterns is thus a vital one in understanding the causes of frequent ozone episodes along the Connecticut coast.

General Meteorological Features. A detailed analysis of wind flow conditions along the Connecticut - Rhode Island coast and in particular in the Groton-New London area, showed that a sea breeze was a very frequent occurrence during July and August. Similar criteria as described for Boston have been used to define sea breeze conditions in the Groton, Connecticut area. However it was more difficult to characterize the sea breeze period from wind data alone. Very seldom did sea breeze winds in the Groton area line-up perpendicular to the coast. The onshore flow was normally from the southwest, being the resultant of a pure southerly sea breeze flow, a Coriolis rotation of the onshore flow and gradient winds from the west or northwest. Other features such as an increase in wind speed and a decrease in relative turbulence (steadying of the wind) were used to establish sea breeze time periods. Temperature and dew point behavior were helpful for this purpose as well. Table 8 provides a good example of the meteorological changes that accompany a well established sea breeze at Groton. The beginning of the sea breeze period at 1300 is clearly marked by a doubling of the wind speed, a sharp reduction in turbulence (σ_θ), a significant drop in temperature, and a two degree rise in the dew point. On this day the onshore flow continued until approximately 2000. As noted earlier, the sea breeze winds were from the southwest direction (250-260°). A clearly definable sea breeze flow seldome developed before 1000 at the WSU Avery Point monitoring site and on many days it was 1200 or after before the onshore flow became fully established. Wind speeds normally began to decrease about 1800 and by 2000 the sea breeze had disappeared.

It was not possible to establish a generalized sea breeze penetration distance from the data collected in July and August 1975. However, in the comprehensive meteorological study conducted by Fisher[5] near Block Island the onshore flow was monitored up to 6 miles inland. Near New York City Frizzola and Fisher[6] found that the sea breeze did not penetrate more than 25 to 30 miles inland.

TABLE 8. METEOROLOGICAL MEASUREMENTS AT GROTON ON JULY 22, 1975.

Time	Wind Direction deg	Wind Speed mph	σθ deg	Temp °F	Dew Point °F
0800	CALM		6	78	65
0900	CALM		7	82	65
1000	CALM		10	85	65
1100	250	5	20	86	65
1200	255	6	13	86	66
1300	250	15	8	80	68
1400	250	17	6	80	70
1500	255	17	5	81	69
1600	255	16	6	82	68
1700	250	13	6	80	68
1800	255	13	6	80	67
1900	260	11	5	77	68
2000	260	9	6	76	68
2100	CALM		10	75	67
2200	CALM		23	73	66
2300	CALM		14	72	67
2400	CALM		8	72	67

General Pollutant Features. High ambient ozone concentrations were frequently observed late in the afternoon at stations in the Groton area. This was particularity true on days when a sea breeze was present. Typically the ozone peak occurred well after the start of onshore flow and during the period of decreasing photochemical activity. Since wind speeds in the sea breeze pattern were usually quite strong (>10 mph) any local accumulation of pollutants would have quickly been dispersed and consequently the most reasonable explanation for the late peaks is advection of ozone-rich air from a distance source.

Air quality data collected in the Groton area on July 22 demonstrate the onshore transport of a highly polluted marine air mass. Table 9 lists ambient pollutart and meteorological data recorded at the WSU monitoring site near Groton. As was pointed out in the previous section, meteorological changes indicated a sea breeze start at about 1200 on the 22nd. Surface ozone concentrations climbed thereafter and remained high until the end of the sea breeze period (~2000). Both WSU and Battelle conducted aircraft sampling missions over southern Connecticut on the afternoon of July 22. These flights showed very conclusively that the area of high ozone resided mainly to the southwest

TABLE 9. SURFACE DATA RECORDED AT GROTON, CT ON JULY 22, 1975.

TIME	O_3	NO	NO_2	[illegible]	CO	CH_4	$CFCl_3$	w/S	w/D	σ_θ	[illegible]	TEMP	DP
hrs	ppb	ppb	ppb	ppm	ppm	ppm	ppt	mph	deg	deg	mW/cm^2	°F	°F
0128	67	12	15	.2	.8	1.6	255	4	235	12	0	73	70
0230	48	12	17	.2	.9	1.6	315	CAL[M]		15	0	73	69
0330	33	12	22	.3	.9	1.6	355	CAL[M]		13	0	72	69
0430	29	12	13	.5	.8	1.6	350	CAL[M]		15	0	71	68
0530	24	12	21	.5	.8	1.6	310	CAL[M]		14	0	70	66
0630	27	12	21	.3	.7	1.6	265	CAL[M]		10	50	71	65
0730	30	12	17	.3	.8	1.6	290	5	270	7	500	72	68
0830	32	14	21	.2	.5	1.6	320	CAL[M]		6	750	78	65
0900	44	17	18	.2	.5	1.6	280	CAL[M]		7	900	82	65
1000	46	10	14	.2	.5	1.6	270	CAL[M]		10	1100	85	65
1100	55	10	13	.2	.5	1.6	185	5	260	20	1275	86	65
1200	59	11	12	.2	.5	1.5	185	6	265	12	1300	86	66
1300	78	11	15	.2	.7	1.6	350	15	250	9	1015	88	69
1400	108	12	16	.3	.8	1.6	500	17	250	6	1375	80	70
1529	121	12	14	.3	.8	1.6	390	17	255	5	1250	81	69
1630	111	11	15	.2	.7	1.6	310	16	255	6	970	82	68
1730	102	9	15	.2	.7	1.6	260	13	250	6	700	80	68
1830	105	7	15	.3	.7	1.6	270	13	255	6	430	80	67
1900	104	10	15	.3	.7	1.6	195	11	260	5	175	77	68
2030	90	11	14	.3	.7	1.6	255	9	260	5	45	76	68
2130	72	11	18	.3	.9	1.6	310	CAL[M]		10	0	75	67
2230	58	11	22	.5	.5	1.6	285	CAL[M]		23	0	73	66
2330	46	11	15	.5	.5	1.6	385	CAL[M]		14	0	72	67
2400	33	12	24	.5	.5	1.6	360	CAL[M]		8	0	72	67

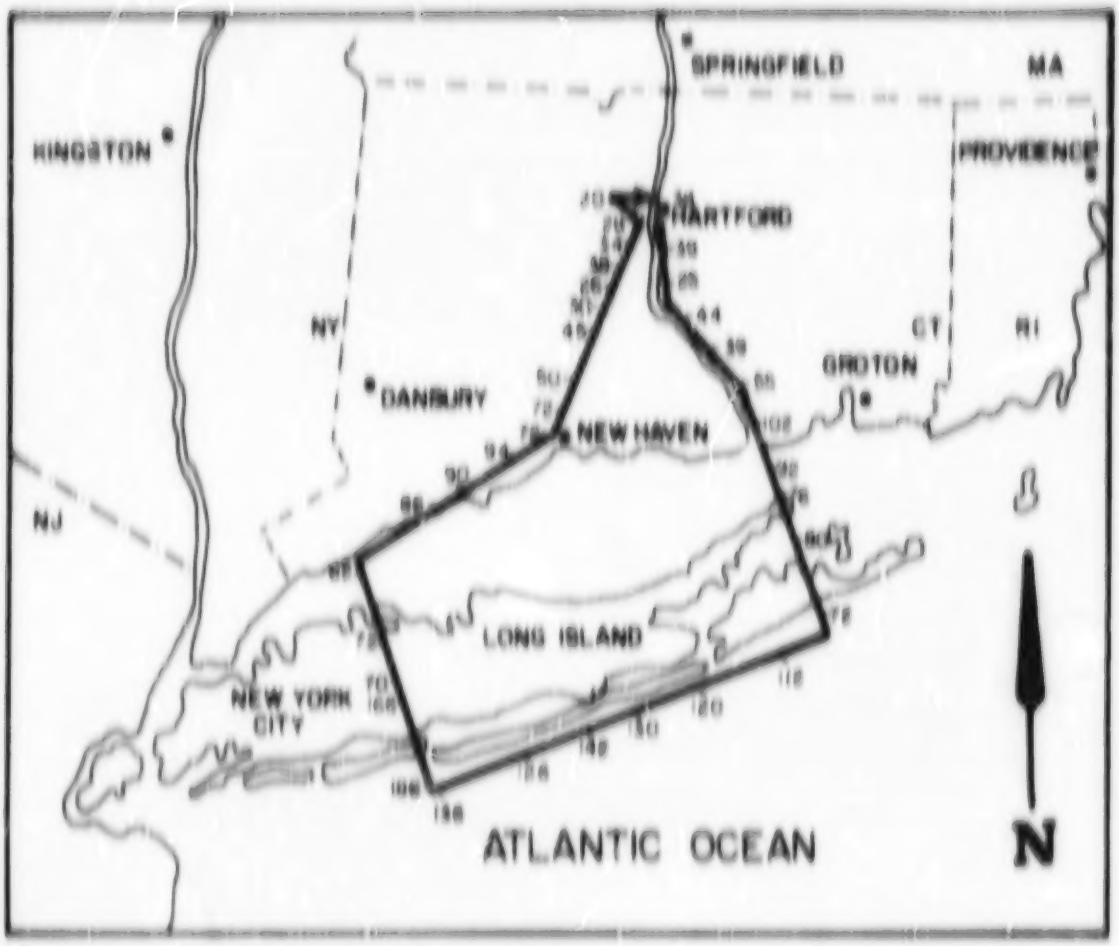

Figure 10. Battelle aircraft flight on afternoon (1400 to 1630) of July 22, 1975, with ozone concentrations (ppb) marked at specific points along the route.

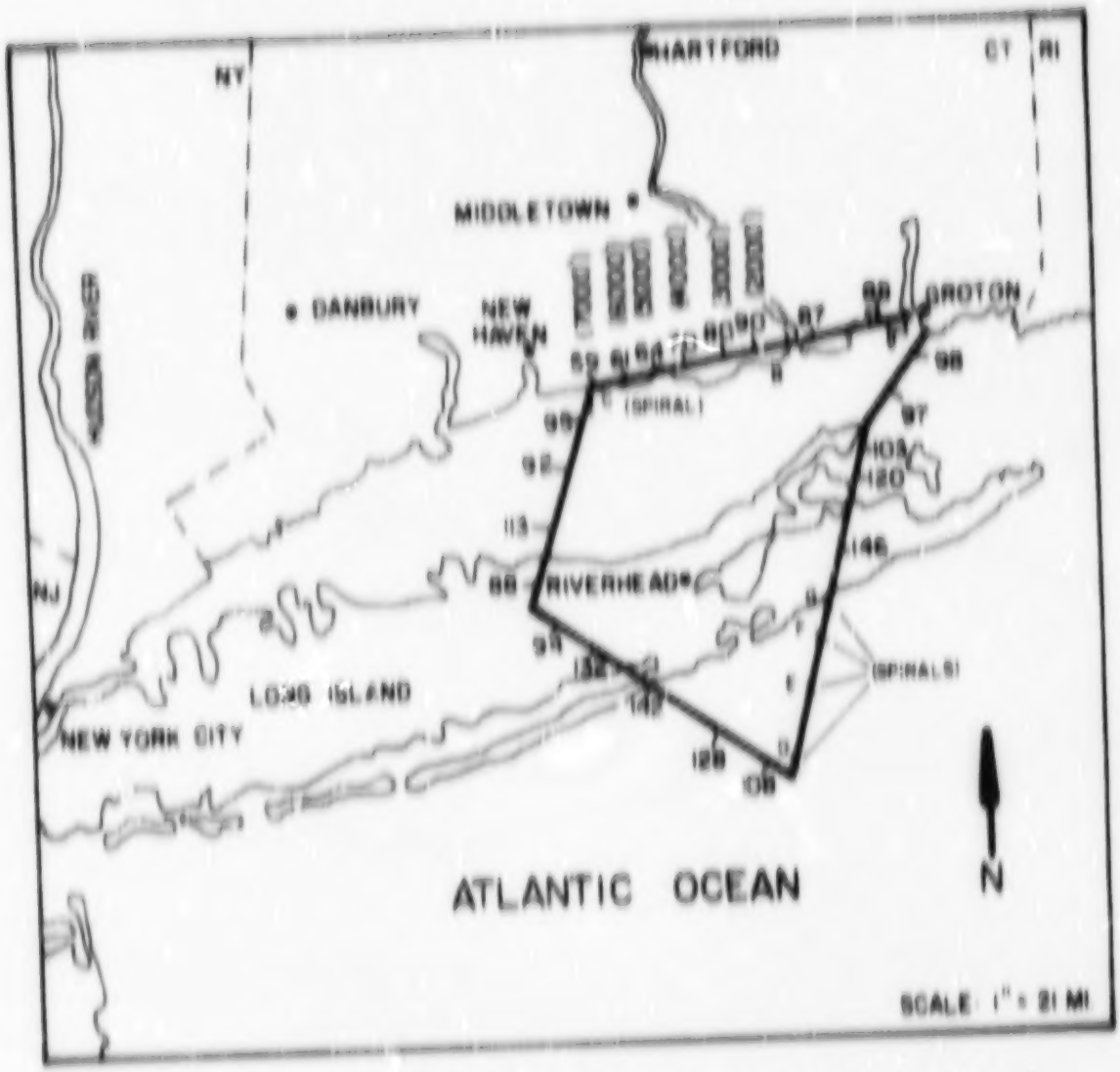

Figure 11. WSU aircraft flight path on the afternoon (1315 to 1555) of July 22, 1975, with ozone concentrations (ppb) marked at specific points along the route.

Figure 12. Surface winds in southern New England at 1500 on July 22, 1975.

of Groton over Long Island and the Atlantic Ocean. Figure 10 shows the Battelle flight path with ozone concentrations (ppb) marked at various points along the route. It is obvious from this figure that ozone concentrations were much lower over Connecticut than those recorded south of Long Island. The WSU afternoon flight (Figure 11) showed ozone levels in the 90-180 ppb range existing over the entire region south and west of Groton. This information when combined with surface wind data at stations in the coastal zone (Figure 12) leaves no doubt that the air quality degradation at Groton resulted from onshore air movement. Furthermore, based on the aircraft data there is little doubt that the contaminated air mass originated in the New York - New Jersey metropolitan area.

For reasons that were cited earlier, it is interesting to trace the history of the polluted air mass arriving at Groton on the afternoon of July 22 based on wind trajectories. This task has been performed by Stanford Research Institute[14] with the results shown in Figure 13. The heavy line and numbers show the route and travel time for the air mass arriving at 1700. It is obvious that the place of origin does not agree with the source area established earlier. In addition, none of the inland monitoring stations along this northwest to southeast route exhibited ozone peaks in excess of 55 ppb on the afternoon of July 22. Thus a trajectory prediction based on gradient wind flow leads in this case and in most others we have examined to an erroneous air mass history.

Before moving on to other examples it is worth noting the effect the July 22 sea breeze had on pollutants other than ozone. Table 9 shows that no discernable difference existed in oxides of nitrogen levels before, during and after the sea breeze period. Likewise the methane and non-methane total hydrocarbon concentrations show little or no change. Fluorocarbon-11 values appear to rise somewhat at the beginning of the sea breeze period. The carbon monoxide concentration remained slightly elevated throughout the period of onshore flow. Thus with the exception of ozone, pollutant levels in the air mass advected into the Groton area on July 22 differed very little from regional background concentrations. This pattern is not suprising considering the fact that the air mass had travelled nearly 80 miles prior to reaching the monitoring station.

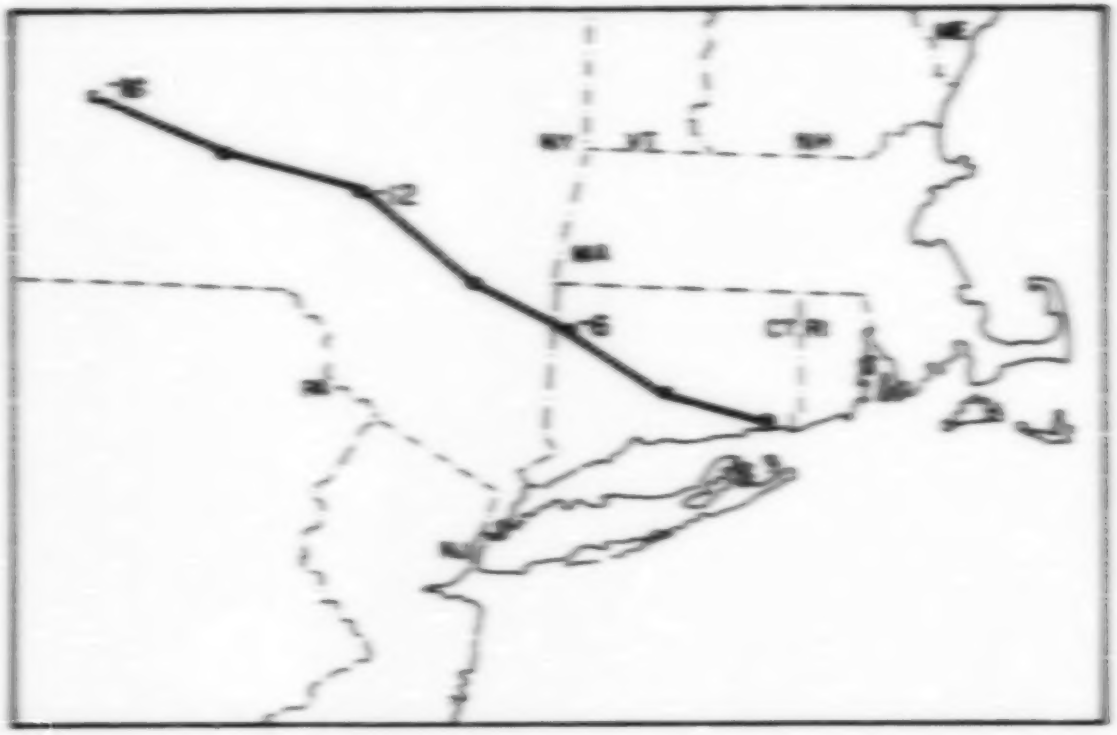

Figure 13. Calculated trajectory (Stanford Research Institute[14]) of air mass arriving at Groton, Connecticut, at 1700 on July 22, 1975.

Pollutant patterns on August 10, 1975 add additional support for the concept of air mass transport from one part of the region to another. At Groton winds were from the west northwest in the early morning and then backed to the west and west southwest at 0800. This wind pattern was the result of a west northwest synoptic flow interacting with a southerly sea breeze condition and brought a flow of ocean air over the Groton area. The marine origin was shown by relatively high dew point temperatures in midday, a midmorning increase in dew point as the sea breeze became established, and the relatively cool afternoon temperature 80° even though the day was clear and sunny. An observed decrease in relative turbulence at Groton occurred during midday and this is also characteristic of the sea breeze regime at this location Table 9 lists air quality data obtained at the WSU monitoring site near Groton on August 10.

A considerable amount of ozone data is available over the area on August 10 as a result of the New England research program. Aircraft flights over Long Island and the Atlantic south of Connecticut showed high concentrations (>100 ppb) at 1000 ft. over both Long Island and the Atlantic before noon (Figure 14). Most ground stations in Connecticut along Long Island Sound also showed O_3 in excess of 100 ppb at 1100 (Figure 15). Later in the day between 1630 and 1830, the time of WSU's afternoon aircraft flight, O_3 concentrations in the lower 1000 ft. over the Atlantic had risen to a range of 190 to 230 ppb (Figure 16). Along the coast as late as 1700 there were still some ground level values of over 100 ppb. At the WSU Groton site the O_3 maximum was especially late and reached 150 ppb in the 2-hour period including 2000 and 2100. At midnight the O_3 concentrations was still 90 ppb.

The pollutant conditions observed on August 10 are a good example, once again, of onshore transport of high pollutant concentrations as well as high O_3 concentrations from an air mass that probably had its origin in the New York City - Northern New Jersey interstate area. The meteorological situation was favorable, obviously, both for the photochemical formation of excessive O_3 in the contaminated lower layers of the atmosphere and for the transport of this polluted air mass inland across the Connecticut coast. This date was another occasion when air mass histories based on regional wind trajectories differed from our evaluation of a sea breeze transport. The trajectory[14] ending at Groton at 1300 on August 10 (Figure 17) moved out of the west northwest while the coastal sea breeze and the New York urban plume came from the west southwest.

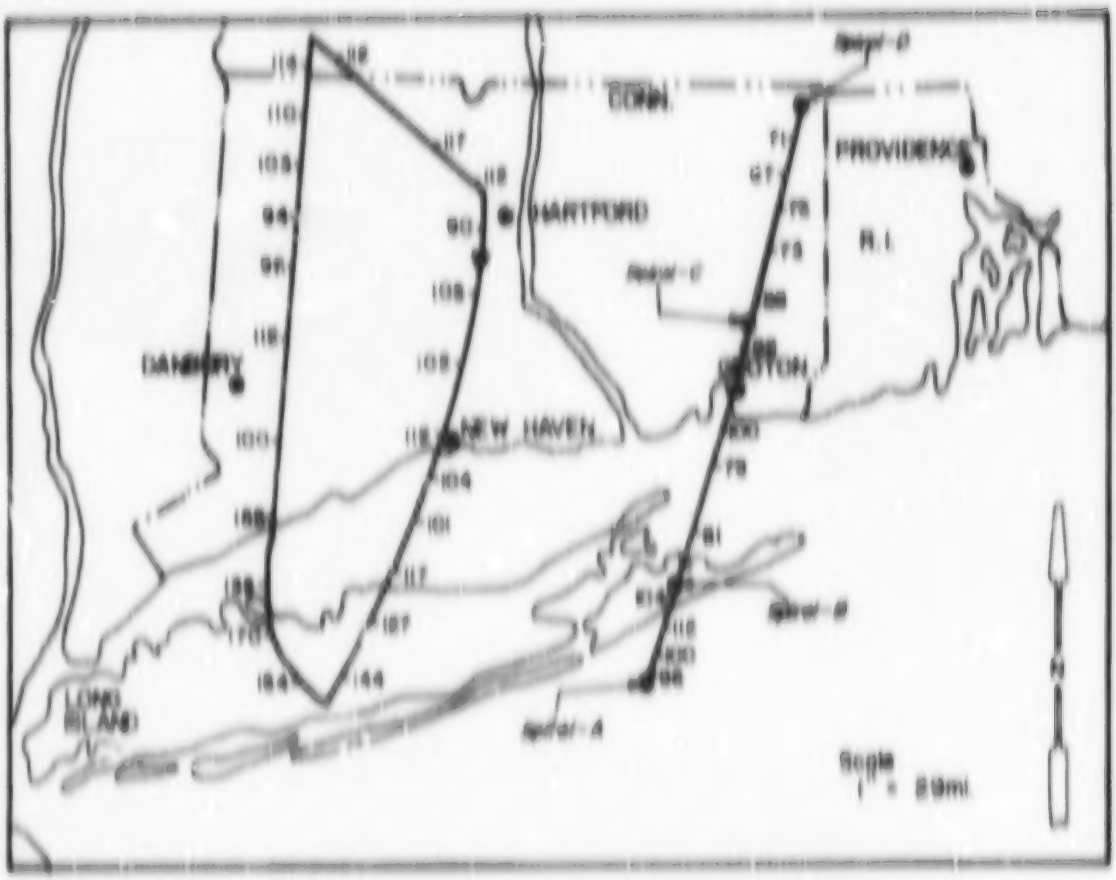

Figure 14. Battelle and WSU flight paths during morning hours on August 10, 1975, with ozone concentrations (ppb) marked at specific points along the route.

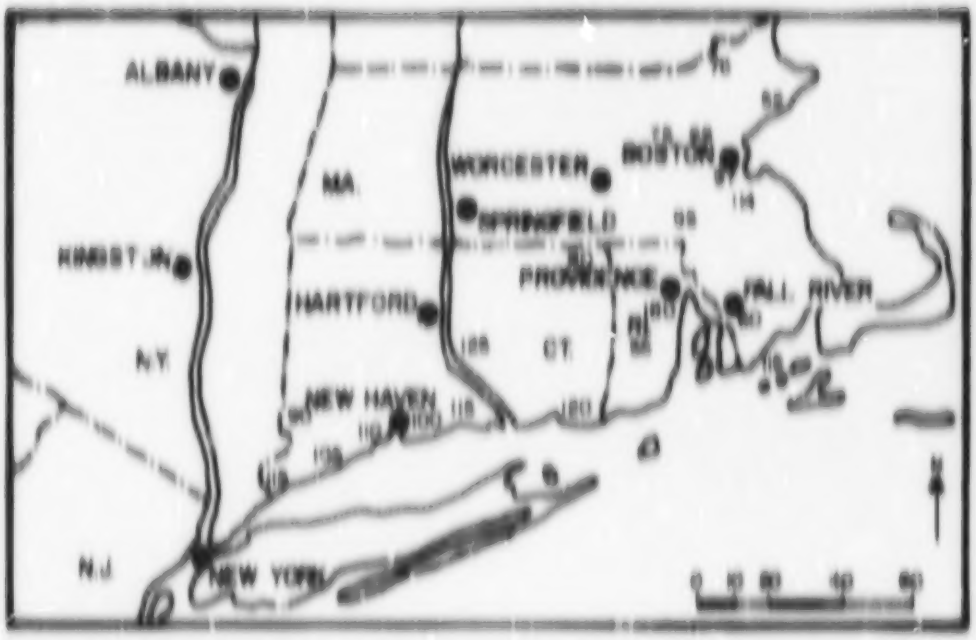

Figure 15. Surface ozone concentrations (ppb) in southern New England at 1100 on August 10, 1975.

Figure 16. Battelle and WSU aircraft flight paths during afternoon hours on August 10, 1975, with ozone concentrations (ppb) marked at specific points along the route.

Along the Connecticut coast it was possible on a few occasions to observe a potential recirculation cell in the sea and land breeze pattern. July 27 was such a day at Groton. Table II shows surface measurements made on this day at Groton, Connecticut. Examination of the wind data indicates that the sea breeze began about 1000 and persisted until about 2100. This is substantiated by the slow temperature rise and the two degree increase in dew point between 0900 and 1000 as the more moist marine air moved onshore. This Groton sea breeze cycle was especially notable because, in the afternoon, the Groton pibal showed a flow reversal or recirculation in the winds aloft. The pibal data recorded at 1510 (Table I2) showed south winds through the lowest 1200 ft. and then a backing of the wind to a northeast direction at 1850 ft. The northeast winds persisted to the top of the mixing layer, about 3400 ft. This pattern is believed to show a complete vertical sea breeze cycle where the onshore or southerly movement of air in the lower layers is compensated for by offshore or northerly winds above the surface layer.

As indicated earlier, a sea breeze recirculation cell provides a mechanism whereby a given air parcel could be carried across the urban area twice and thus produce an accentuated pollutant pattern. On July 27 at the WSU Groton site (Table II) O_3 concentrations gradually increased during the morning to peak values of 71 and 73 ppb at 1300 and 1400. After 1400, O_3 levels dropped but did not go below 60 ppb until 2200. Halocarbon measurements (Fluorocarbon-11) showed that general pollutant levels on the 27th in the afternoon were relatively low , and thus the afternoon O_3 concentrations of over 60 ppb were accompanied by relatively clean air. The O_3 pattern along the Connecticut coast west of Groton (Figure 18) varied some in the value of the mid-day O_3 maximum compared to Groton, but the pattern observed at Groton seems typical of much of the Connecticut coast. The major differences occurred in the extreme west, bordering New York City, where the urban plume effect could be seen.

This episode seems to show that when conditions at Groton are such that a strong recirculation sea breeze cycle can develop, the accompanying overall pollutant pattern is characterized by only low to moderate levels of O_3 and other pollutants. Although a single example is obviously insufficient to prove this correlation, basic features of the sea breeze pattern would favor such a conclusion. First, along the Connecticut coast a well developed

TABLE 12. PIBAL DATA FROM GROTON, CONNECTICUT, AT 1510 ON JULY 27, 1975

Layer height mid-point (ft)	Wind direction (degrees)	Wind speed (mph)
177	185	5
531	190	4
863	198	2
1000	192	3
1186	183	3
1515	109	1
1840	052	4
2000	047	5
2317	037	6
2775	004	6
3000	010	3
3085	024	2
3382	065	2
3678	127	3
3975	171	1
4000	172	2
4408	198	6
4862	171	8
5000	166	7
5453	168	7
5749	163	5
6000	177	2
6044	179	2
6340	164	3
6636	316	7
6931	224	4
7000	218	5

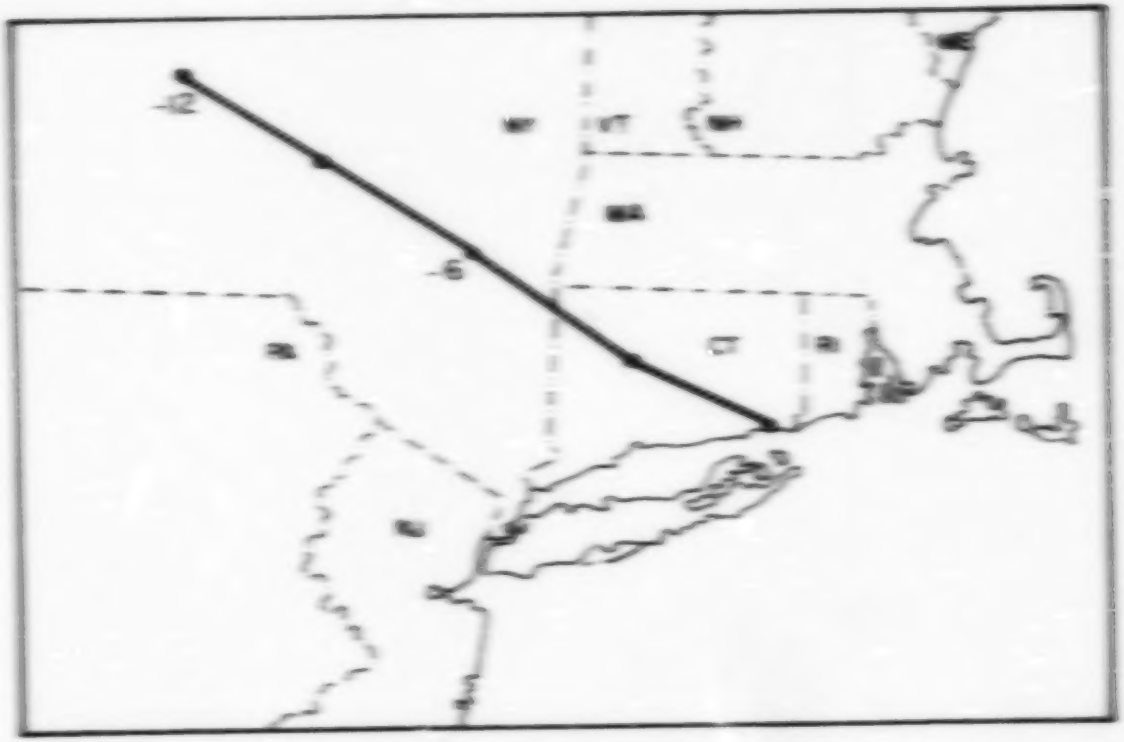

Figure 17. Calculated trajectory (Stanford Research Institute[14]) of air mass arriving at Groton, Connecticut at 1300 on August 10, 1975.

circulation pattern will have a deep mixing layer and thus would tend to lessen the impact of pollutant sources. Second, the presence of a local recirculation system could probably not be detected if regional advection were also taking place, and thus the levels of pollutants present in the recirculation systems are going to be dependent primarily on local, not advected sources. In the Groton area and along much of the adjacent coast, local sources are not large.

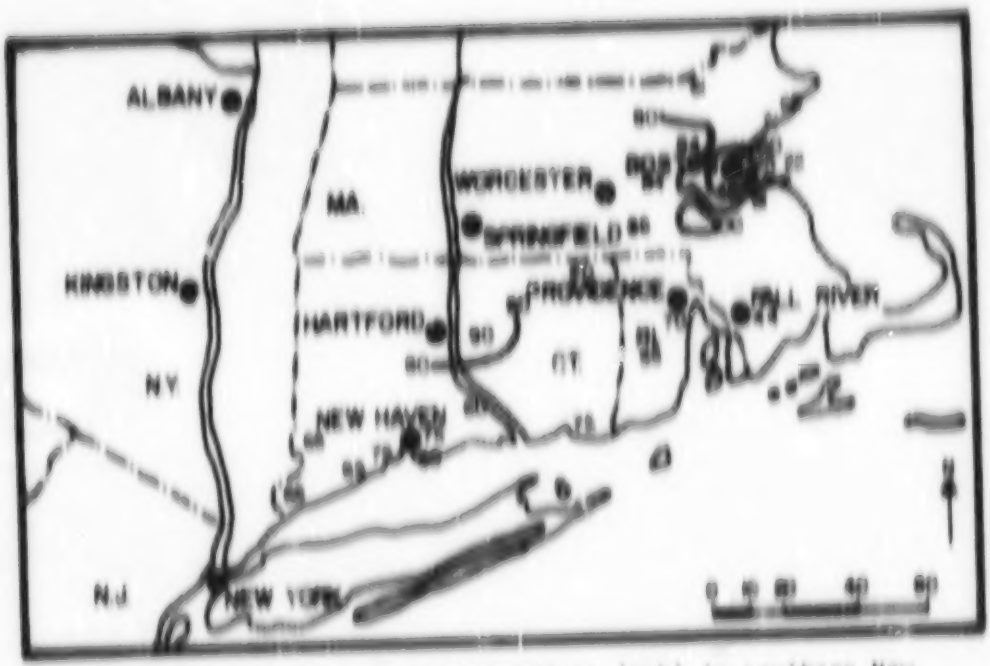

Figure 18. Surface ozone concentrations (ppb) in southern New England at 1300 on July 07, 1975.

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